CIRP Annals - Manufacturing Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Study of stress intensity factor on the anisotropic machining behavior of single crystal sapphire

Hae-Sung Yoon, Suk Bum Kwon, Aditya Nagaraj, Seola Lee, Sangkee Min (2)*

Department of Mechanical Engineering, University of Wisconsin-Madison, 1513 University Avenue, Madison, WI 53706, USA

ARTICLE INFO

Keywords:
Machinability
Brittleness
Sapphire

ABSTRACT

The ductile–brittle transition was investigated based on material crystallography and stress intensity factor on the four distinctive planes of sapphire. Cutting forces were analyzed to explain the anisotropic transition characteristics. The projected stress on the objective plane at the transition point was estimated from the critical stress intensity factor of the corresponding crystal plane. Per cutting direction, the effect of crystal planes on the machinability was discussed, and the estimated stress was compared with measured values. Experimental results showed that the anisotropic machinability can be predicted in terms of crystal orientation and the critical stress intensity factor.

1. Introduction

Transition of material removal behavior has been investigated in machining of engineering materials. The material response can drastically change from ductile to brittle regimes with respect to the scale of deformation, temperature, pressure conditions, *etc.* [1,2]. Particularly at nano-scale depth of cut, ductility can be the matter of the deformation size. In many materials generally considered as brittle and difficult-to-cut, ductile mode cutting has been observed and investigated at a very small depth of cut [3].

Ductile mode cutting enables efficient processing as it can provide better surface quality with low sub-surface damage. It can also handle the creation of more complex features with higher productivity than commonly adopted loose abrasive processes [4]. Thus, machining characteristics and the applicability of ductile mode cutting have been investigated in many engineering ceramics, such as sapphire (α-Al_2O_3) [5], calcium fluoride (CaF_2) [6], and KDP crystal (KH_2PO_4) [7].

However, it is still not straightforward to control the ductile behavior in machining of those ceramics, since the material behavior and crack initiation mechanisms are not fully understood and explained. Particularly during the cutting, parameters and mechanisms that activate different removal behaviors have not been clearly identified yet. Therefore, it is required to formulate a model that can describe and predict the ductile–brittle transition to promote ductile mode cutting.

As the preliminary study, machining characteristics on basal plane (*C*-plane) of single crystal sapphire has been studied with respect to its crystallography [5]. In ultra-precision orthogonal cutting, the ductile–brittle transition points were observed and discussed in terms of different cutting directions. Authors presented ductile and brittle deformation parameters based on geometric relationships between cutting directions and each crystallographic plane.

However, it is required to quantitatively explain the anisotropic tendency of the ductile–brittle transition. Ductile and brittle deformation parameters could only show tendencies among different crystallographic planes. Crack initiation parameters need to be identified to predict the transition.

Therefore, more comprehensive and quantitative analysis was performed in this study. Orthogonal cutting experiments were extended to the four primary planes of sapphire (*C*-, *A*-, *M*-, and *R*-planes). In addition to crack morphologies, stress at the transition point was analyzed to explain anisotropic transition characteristics. Based on given material properties and crystallographic information, the critical stress to the weakest direction was derived and compared with experimental results. Through the research, ductile–brittle transition characteristics were observed and analyzed. It is expected that this research can contribute to understanding of material behavior at very small scale, thus the development of machining strategies for ceramics.

2. Stress intensity factor analysis

Sapphire has a hexagonal unit-cell structure of 3-fold symmetry. Fig. 1 shows a crystal form of sapphire and primary crystal planes, and Fig. 2 shows angular relationships between these planes. Orthogonal cutting was performed in various directions on each crystal plane.

In this research, stress during the cutting was hypothesized to influence the crack initiation on different crystal planes simultaneously. Material deformation and fracture then occurred on the weakest crystal planes. Here, the stress intensity factor was calculated and compared with other known properties to explain crack initiation.

Stress intensity factor represents severity of the stress state, and mode I (crack opening under the tensile load) stress intensity

---

* Corresponding author.
E-mail address: sangkee.min@wisc.edu (S. Min).

https://doi.org/10.1016/j.cirp.2018.04.114

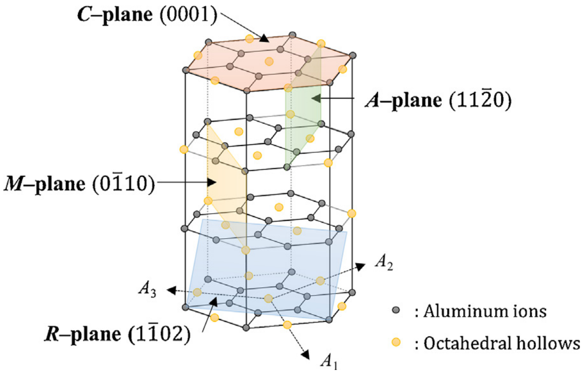

Fig. 1. Crystal form and primary crystal planes of sapphire [9].

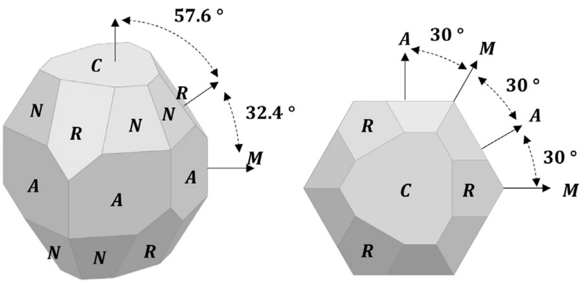

Fig. 2. Angular relationships between primary crystal planes.

factor K_I can be calculated as follows [8]:

$$K_I = \sigma_N \cdot \sqrt{\pi a} \cdot G \tag{1}$$

where σ_N is the tensile stress applied to the normal direction of crystal plane, a is the length of an initial flaw, and G is the constant that describes geometric positioning of the initial flaw to applied stress. For simplicity, the term G was assumed to be the same regardless of the cutting direction or crystal plane. Then, the stress at the transition point can be conversely estimated from the critical stress intensity factor K_{Ic}. Table 1 shows the critical stress intensity factor of single crystal sapphire.

Table 1
Critical stress intensity factor of crystal planes of sapphire [10,11].

Planes	Miller–Bravais indices	Critical stress intensity factor K_{Ic} [MPa m$^{-1/2}$]
C-plane	(0001)	6.043
A-plane	{1$\bar{2}$10}	2.509
M-plane	{1$\bar{1}$00}	3.140
R-plane	{1$\bar{1}$02}	2.380

Then the normal stress, σ_N, can be represented as follows:

$$\sigma_N = \sigma \cdot \cos^2 \theta \tag{2}$$

where σ is the stress in the cutting direction, and θ is the angle that the cutting direction forms with the normal direction of corresponding crystal plane.

In this study, the corresponding crystal plane was identified for each cutting direction by searching the lowest values among critical stress intensity factors projected in each cutting direction. Then, at the transition point, the stress normal to the corresponding crystal plane was estimated and compared with measured values from experiments. Sometimes, the plane with higher critical stress intensity factor may be activated, as the thrust force may suppress the normal stress of a certain plane. By analyzing the stress, its influence on crack initiation can be quantitatively analyzed.

3. Experiments

3.1. Experimental details

An ultra-precision machine tool (ROBONANO α-0iB, FANUC Corp., Japan) was used to cut sapphire (produced by Czochralski technique, M.T.I Corp., U.S.A), as the ductile–brittle transition usually occurs at the depth of cut of hundreds of nanometers [5]. A nano-polycrystalline diamond tool (A.L.M.T. Corp., Japan) with a nose radius of 500 μm was used. Cutting forces were measured using a dynamometer (Type 9119AA1, KISTLER Instrument Corp., Switzerland) and multi-channel amplifier (Type 5080A, KISTLER Instrument Corp., Switzerland) with a low pass filter. Fig. 3 shows hardware configurations used in the experiments. Cutting was performed on C-, A-, M-, and R-plane, respectively.

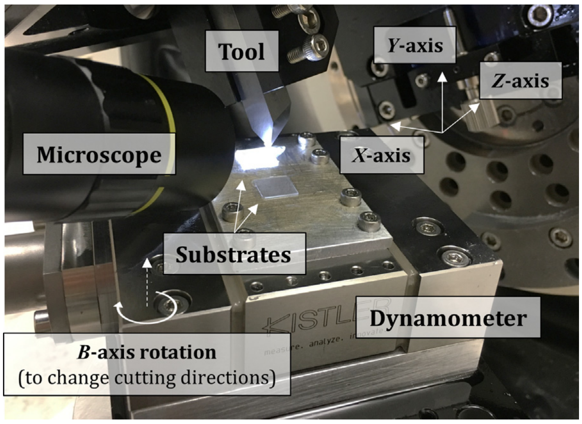

Fig. 3. Hardware configurations of experiments.

On each plane, plunge cuts were performed with an angle of 0°–330° with a 30° interval. Each path was designed to have a slope of 1/500, and a feed of 5 mm min^{-1} was used. All path was repeated at least three times. Similar to the preliminary studies [5], critical depth of cut, the depth of cut where the first significant crack occurs, were measured and compared. Fig. 4 shows a schematic of the cutting path and an example of morphology change in ductile–brittle transition. Cracks are clearly shown in the brittle region after the transition point.

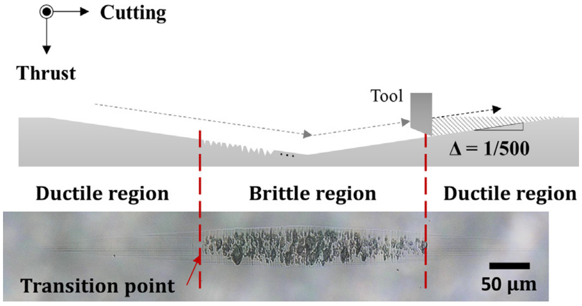

Fig. 4. A schematic of tool path and machined example.

Fig. 5 shows a corresponding cutting force signal of the slot in Fig. 4. F_y is the cutting force, and F_z is the thrust force acting down into the substrate. The ductile–brittle transition is clearly observed. Both cutting and thrust forces linearly increases as the depth of cut increases, then suddenly largely vibrate after the transition point. The critical depth of cut was observed and determined by combining the results from optical images, cutting forces signals, and depth morphology.

Forces and morphology characteristics are significantly different in terms of cutting directions, and they indicate how cracks open on a certain crystal plane. Sometimes, ductile–brittle transition was not clearly shown in force signal as much as shown in Fig. 5. However, rather than going deep into individual cutting direction, overall characteristics of ductile–brittle transition were mainly discussed in this research.

Please cite this article in press as: Yoon H-S, et al. Study of stress intensity factor on the anisotropic machining behavior of single crystal sapphire. CIRP Annals - Manufacturing Technology (2018), https://doi.org/10.1016/j.cirp.2018.04.114